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CGRO Guest Investigator Program – Cycle 8

Broad-Band Gamma-Ray Spectra of Cygnus X-1

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Summary

The data collected by the COMPTEL experiment on CGRO provides an unprecedented opportunity to study the high energy spectrum of the galactic black hole candiadte Cygnus X-1. A proper interpretation of the high energy spectrum, however, requires simultaneous knowledge of the spectrum at lower energies. Taken collectively, the instruments on CGRO afford the capability to study the nature of the broad band high energy spectrum of Cygnus X-1. This program is intended to more fully analyze the numerous observations of Cygnus X-1 that have been conducted during the course of the CGRO mission. In the past, these studies have been somewhat hindered by discrepancies between the spectra measured with BATSE and OSSE. We have recently been able to move beyond this problem to provide a more detailed analysis of the Cygnus X-1 spectrum and its variability at MeV energies.

The COMPTEL Observations

COMPTEL has observed Cygnus X-1 numerous times during the CGRO mission. The table below lists all of the available observations as of September, 1999. Many of these observations took place when Cygnus X-1 was placed at an unfavorable zenith angle (ZA). Unfavorable values are typically considered to be anything greater than 30°. These observations may, however, still conatin useful data, especially if Cygnus X-1 is brighter than average.

VP	FIELD	DATES	GLONG	GLAT	Z.A.	EXPOS
		(degrees)	(days)			
2.0	Cyg X-1	91-05-30 to 91-06-08	73.00	3.00	1.7	3.65
7.0	Cyg X-3	91-08-08 to 91-08-15	70.00	-8.00	11.1	2.72
9.5	Her X-1	91-09-12 to 91-09-19	60.00	40.00	38.3	0.69
20.0	SS 433	92-02-06 to 92-02-20	40.00	1.00	31.3	2.19
34.0	CAS A	92-07-16 to 92-08-06	109.00	-2.00	38.0	0.85
201.0	Her X-1	92-11-17 to 92-11-24	67.00	39.00	36.1	0.31
202.0	Her X-1	92-11-24 to 92-12-01	71.00	40.00	36.9	0.31
203.0	Cyg X-3	92-12-01 to 92-12-08	78.00	1.00	7.0	1.75
203.3	Cyg X-3	92-12-08 to 92-12-15	78.00	1.00	7.0	1.75
203.6	Cyg X-3	92-12-15 to 92-12-22	78.00	1.00	7.0	1.69
212.0	WR 140	93-03-09 to 93-03-23	84.00	12.00	15.4	2.71
302.0	N Cyg 1992	93-09-07 to 93-09-09	89.00	8.00	18.3	0.32
303.2	N Cyg 1992	93-09-22 to 93-10-01	89.00	8.00	18.3	1.43

303.7	N Cyg 1992	93-10-17	to	93-10-19	89.00	8.00	18.3	0.32
318.1	Cyg X-1	94-02-01	to	94-02-08	68.00	0.00	4.5	1.78
328.0	PSR 1951+32	94-05-24	to	94-05-31	65.00	0.00	7.0	1.57
331.0	PSR 1951+32	94-06-07	to	94-06-10	65.00	0.00	7.0	0.95
331.5	PSR 1951+32	94-06-14	to	94-06-18	65.00	0.00	7.0	1.34
333.0	PSR 1951+32	94-07-05	to	94-07-12	65.00	0.00	7.0	1.87
403.0	Her X-1	94-11-01	to	94-11-09	58.00	38.00	37.0	0.54
410.0	Gal 082-33	95-01-24	to	95-02-14	82.00	-33.00	37.5	1.42
429.5	GRO J2058+42	95-09-27	to	95-10-03	86.00	-13.00	21.7	1.19
506.0	Cas A-1	95-11-07	to	95-11-14	111.00	5.00	39.6	0.51
503.0	Cas A-3	95-11-14	to	95-11-21	104.00	-2.00	33.1	0.85
516.5	MRK 501	96-03-21	to	96-04-03	58.00	39.00	37.9	1.13
519.0	3C 345	96-04-23	to	96-05-07	63.00	40.00	37.7	1.24
522.5	Cyg X-1	96-06-14	to	96-06-25	66.00	3.00	5.3	2.75
601.1	PSRJ2043+274	96-10-15	to	96-10-29	70.00	-11.00	14.1	3.52
612.1	Cyg X-1	97-01-28	to	97-02-04	71.00	3.00	0.3	2.02
617.8	MRK 501	97-04-09	to	97-04-15	67.00	37.00	34.2	0.57
619.2	GRS1915	97-05-14	to	97-05-20	47.00	-1.00	24.6	0.91
623.5	BL Lac	97-07-15	to	97-07-22	93.00	-10.00	25.3	1.21
703.0	Gal 035+20	97-11-25	to	97-12-02	35.00	19.00	38.9	0.56
704.0	Gal 035+20	97-12-02	to	97-12-09	35.00	14.00	37.5	0.60
710.0	J1835+5919	98-01-13	to	98-01-21	86.00	29.00	29.5	1.22
711.0	J1835+5919	98-01-21	to	98-01-27	86.00	29.00	29.5	0.86
720.5	GRS1915+105	98-05-05	to	98-05-15	45.00	0.00	26.5	1.65
721.0	MRK 501	98-05-15	to	98-05-19	64.00	39.00	36.5	0.38
722.5	MRK 501	98-05-22	to	98-05-27	64.00	39.00	36.5	0.40
732.5	GAL 058-12	98-09-15	to	98-09-22	58.00	-13.00	20.8	1.43
737.0	GAL 044-09	98-11-24	to	98-12-01	44.00	-9.00	29.8	1.05
804.0	GC Scan	98-12-22	to	99-01-05	62.00	-5.00	12.3	2.96
811.5	GRS 1915+105	99-04-06	to	99-04-13	42.00	4.00	29.3	0.99
812.5	GRS 1915+105	99-04-13	to	99-04-20	42.00	4.00	29.3	0.87
813.5	GRS 1915+105	99-04-20	to	99-04-27	42.00	3.00	29.3	0.76
827.0	Cygnus	99-08-17	to	99-08-31	92.00	6.00	20.8	2.94
828.0	Cygnus	99-08-31	to	99-09-14	86.00	9.00	15.8	2.78

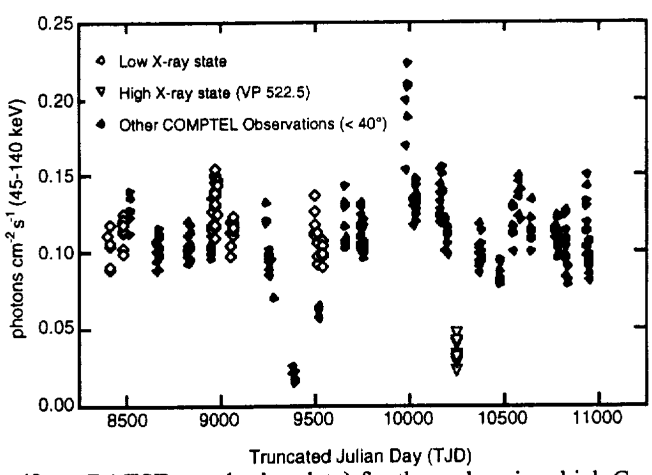

Figure 1. Hard X-ray flux (from BATSE occultation data) for those days in which Cygnus X-1 was being observed by COMPTEL. The days with open diamonds are those days used to generate the low X-ray state spectrum in Figure 2. The days with open triangles are those days used to generate the high X-ray state spectrum in Figure 3.

Broad-Band Spectrum of Cygnus X-1 in its Low X-Ray State

Cygnus X-1 spends most of its time in the so-called low X-ray state. The hard X-ray flux (~100 keV) is generally anticorrelated with the soft X-ray flux (~10 keV), so the hard X-ray flux during this state is relatively high. The hard X-ray spectrum of this state can be characterized as a "breaking" spectrum, based on the general classification scheme proposed by Grove (1998). We have compiled a broad-band spectrum based on contempoarneous data from BATSE, OSSE and COMPTEL collected during the first three phases of the CGRO mission. The days used for this compilation are denoted by open diamonds in Figure 1. The BATSE data used here are taken from the JPL-EBOP analysis, as provided by co-investigator Jim Ling (NASA/PJL). The OSSE data have been provided by co-investigvator Bernard Phlips (George Mason Univ.). The compiled spectrum is shown in Figure 2, where we also include an estimated uper limit from EGRET based on information provided in the 3rd EGRET source catalog.

At lower energies (below several hundred keV), the spectrum can be described as a Comptonization spectrum. At higher energies, however, the spectrum deviates considerably from a Comptonization spectrum, exhibiting a hard tail extyending into the MeV region. The COMPTEL data shows evidence for this tail up to at least 2 MeV and perhaps 5 MeV. The tail can be described as a power loaw with a photon spectral index of –3.2. There is no evidence for a cutoff to this extended tail, either from the higher energy COMPTEL data or from the EGRET data. This spectrum promises to be very useful in modeling the emission from Cygnus X-1 and, in particular, in studying the origin of the hard tail at energies near 1 MeV and above.

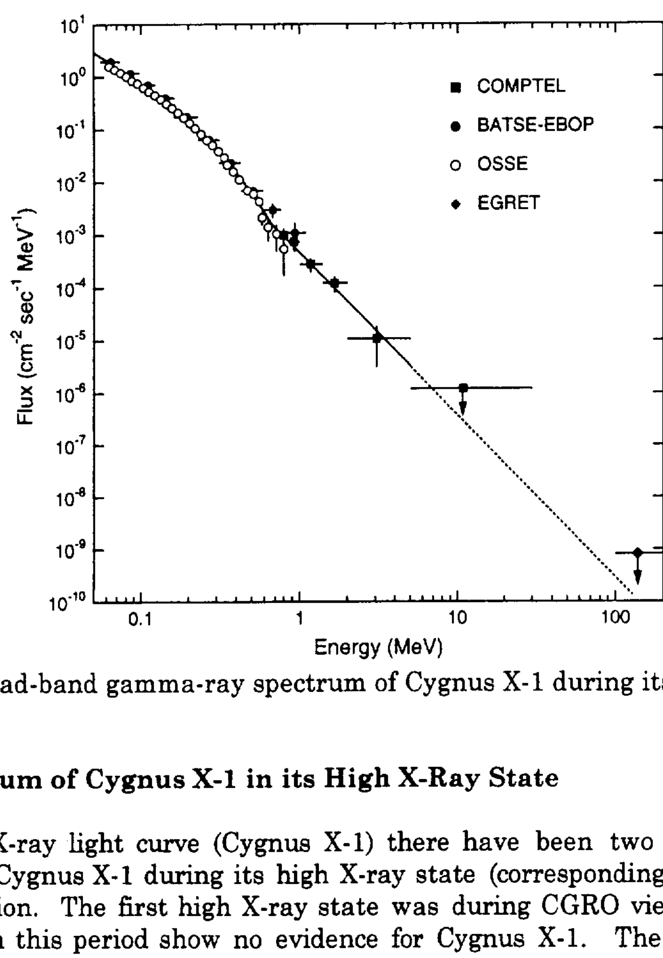

Figure 2. Broad-band gamma-ray spectrum of Cygnus X-1 during its low X-ray state.

Broad-Band Spectrum of Cygnus X-1 in its High X-Ray State

Based on the hard X-ray light curve (Cygnus X-1) there have been two ocassions during which COMPTEL observed Cygnus X-1 during its high X-ray state (corresponding to a period of relatively low hard X-ray emission. The first high X-ray state was during CGRO viewing period 318.1. The COMPTEL data from this period show no evidence for Cygnus X-1. The lower-energy data from

BATSE and OSSE show a power-law spectrum that, when extended into the COMPTEL energy range, falls below the sensitivity of the COMPTEL observation.

A second high X-ray state observation took place in June of 1996 (CGRO viewing period 522.5). The low energy spectrum again exhibited a power-law form, but the intensity of the power-law was sufficiently high so that the emission could also be seen by COMPTEL. Indeed, the COMPTEL detection during this observation was one of the most significant single-observation detections ever made by COMPTEL. The COMPTEL data for this observation exhibited a much harder spectrum than that measured during the low X-ray state (Figure 2). Combined with contemporaneous OSSE data, the spectrum shows a continuous power-law extending from 50 keV up to ~10 MeV, with only a marginal hint a t a break in the power-law at energies near 10 MeV. (No BATSE-EBOP data were available at this time and we have yet to acquire a spectrum from the BATSE occultation data.) This type of spectral evolution, varying between a "breaking-type" spectrum during the low soft X-ray state and a power-law spectrum durung the high soft X-ray state, has already been seen by OSSE in several galactic black hole candidates, including Cygnus X-1. The data from COMPTEL extend this picture, for the first time, to energies above 1 MeV.

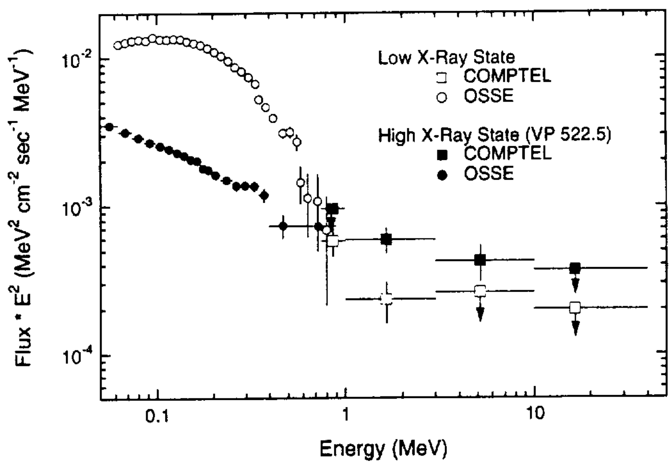

Figure 3. A comparison of the broad-band spectrum of Cygnus X-1 collected during the low soft X-ray state (same data as in Figure 2) and a high soft X-ray state (VP 522.5). This type of spectral evolution has not been studied before at energies above 1 MeV.

Future Work

We are continuing our studies of CGRO data on Cygnus X-1 in an effort to understand not only the nature of the broad-band gamma-ray spectrum, but also the variability of this spectrum. Several recent high-quality observations of Cygnus X-1 have been obtained by COMPTEL and it is expected that the results presented here can be further improved upon with continued analysis. We are also in the process of a more careful study of the data collected during the high X-ray state of VP 522.5, where we plan to include data from BATSE in our future studies.

Recent Publications

The latest results from this study have been published in the following papers. Copies of the first two papers are attached to this report. The third paper is close to being submitted to the Astrophysical Journal.

1) *The MeV Gamma-Ray Specrum of Cygnus X-1*

M.L. McConnell, K. Bennett, H. Bloemen, W. Collmar, W. Hermsen, L. Kuiper, J.C. Ling, B. Phlips, J.M. Ryan, V. Schönfelder, H. Steinle, and A. Strong 1999, Proc. 26th Internat. Cosmic Ray Conf., Durban (Salt Lake City, UT), 4, 119.

2) *The Spectral Variability of Cygnus X-1 at MeV Energies*
M.L. McConnell, K. Bennett, H. Bloemen, W. Collmar, W. Hermsen, L. Kuiper, B. Phlips, J.M. Ryan, V. Schönfelder, H. Steinle, and A. Strong 2000, to be published in AIP Conf. Proc., "Proceedings of the Fifth Compton Symposium", ed. M.L. McConnell & J.M. Ryan (New York: AIP).

3) *A High Sensitivity Measurement of the MeV Gamma-Ray Spectrum of Cygnus X-1*
M.L. McConnell, K. Bennett, H. Bloemen, W. Collmar, W. Hermsen, L. Kuiper, J.C. Ling, B. Phlips, J.M. Ryan, V. Schönfelder, H. Steinle, and A. Strong 2000, Ap.J., in preparation. (A draft of this paper has recently been distributed to the co-authors. It is hoped that the final version will be submitted to Ap.J. by the end of 1999.)

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The MeV Gamma-Ray Spectrum of Cygnus X-1

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Abstract

The COMPTEL experiment on the Compton Gamma-Ray Observatory (CGRO) has observed the Cygnus region on several occasions since its launch in 1991. These data represent the most sensitive observations to date of Cyg X-1 in the 0.75-30 MeV range. Here we report on the results of an analysis of selected COMPTEL data collected during the first three years of the CGRO mission. The integrated spectrum shows significant evidence for emission extending out to several MeV. These data are compared with contemporaneous data from both BATSE and OSSE.

1 Introduction:

It has become increasingly apparent over the last several years that the standard thermal Comptonization model (Sunyaev & Titarchuk 1980) does not provide an adequate description of the broad-band spectrum of Cyg X-1. Several modifications to the standard model have been proposed that seek to provide a better fit to the data. For example, modifications to the standard model have been developed which expand the range of allowable parameter space (e.g., Titarchuk 1994; Hua & Titarchuk 1995; Skibo et al. 1995). Other models have pursued alternative geometries that can also lead to improvements in the model. These include the incorporation of Compton backscatter radiation from a cooler optically-thick accretion disk (Haardt et al. 1993; Wilms et al. 1996) or models based on a thermally stratified geometry (e.g., Skibo & Dermer 1995; Ling et al. 1997a; Moskalenko, Collmar & Schönfelder 1998). Still others have proposed schemes which are based on nonthermal acceleration processes (e.g., Li, Kusunose & Liang 1996; Crider et al. 1997) or π° decay (Jourdain & Roques 1994). All of these models have their merits. Unfortunately, given the quality of the available data, it is difficult to determine a clearly favored candidate to account for the observed spectrum near 1 MeV. In this regard, the data collected by the instruments on CGRO offer the best opportunity for studying the high energy spectrum of Cyg X-1.

2 Observations and Data Analysis:

To date, COMPTEL has obtained numerous observations of the Cygnus region. Most of the high-quality (i.e., near on-axis) observations took place during the first three years of the mission. Here, we have selected a subset of these data for analysis (Table 1). This choice of observations was dictated by the availability of contemporaneous OSSE. These data, along with contemporaneous results from BATSE, were used to assemble a broad-band spectrum extending well above 1 MeV. Discrepancies in the initial comparison of the three spectra (McConnell et al. 1997) were later attributed to variations in the source spectrum coupled to variations in the relative exposure time of each instrument. Consequently, data from some of these observations (VP 318.1 and VP 331.5) were later excluded from the analysis, based on the level of hard X-ray flux as measured by BATSE occultation analysis (Figure 1). This selection insures that all data were collected while Cyg X-1 was in the same spectral state.

TABLE 1 – SELECTED CGRO OBSERVATIONS

Viewing Period	Start Date	Start TJD	End Date	End TJD	Viewing Angle	Effective Exposure
2.0	30-May-1991	8406	8-Jun-1991	8415	1.7°	3.65
7.0	8-Aug-1991	8476	15-Aug-1991	8483	11.2°	2.72
203	1-Dec-1992	8957	22-Dec-1992	8978	7.0°	5.19
212.0	9-Mar-1993	9055	23-Mar-1993	9069	15.4°	2.71
318.1	1-Feb-1994	9384	8-Feb-1994	9391	4.5°	1.78
328.0	24-May-1994	9496	31-May-1994	9503	7.0°	1.56
331.0	7-Jun-1994	9510	10-Jun-1994	9513	7.0°	0.95
331.5	14-Jun-1994	9517	18-Jun-1994	9521	7.0°	1.34
333.0	5-Jul-1994	9538	12-Jul-1994	9545	7.0°	1.86

The analysis of COMPTEL data involves generating a series of images, one for each energy interval of interest. Assumptions regarding the spectral shape are incorporated into the point-spread-functions (PSFs) used in the analysis of each image. Flux values derived from each image are used to compile a spectrum of the source. The resulting spectrum is then compared versus that assumed for the PSF generation to insure a consistent analysis. The COMPTEL image analysis for Cyg X-1 is complicated by the fact that we are looking in the galactic plane. Images generated with COMPTEL data generally show some level of spatial structure, much of which is believed to result from galactic diffuse emission. In the present case, the spatial analysis of each energy interval was performed independently using a variety of spatial distributions. These

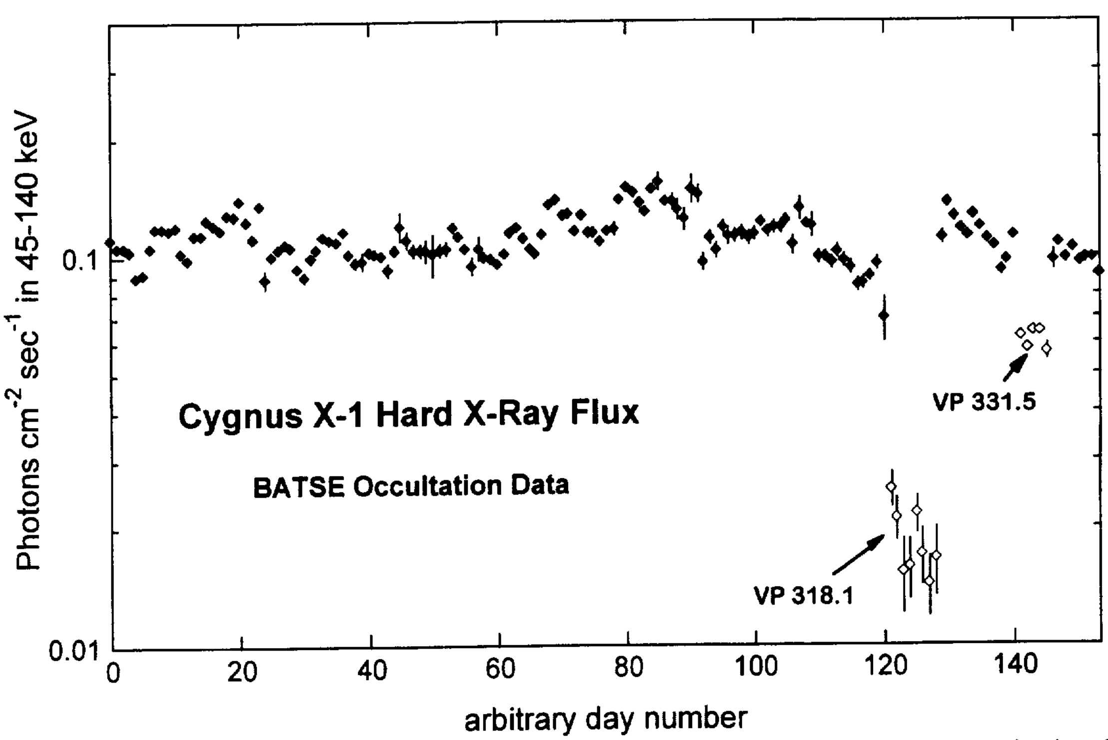

Figure 1: The hard X-ray flux of Cyg X-1 as measured by BATSE occultation monitoring for those days represented by the observations in Table 1. The two observation periods with relatively low hard X-ray flux were excluded from the final analysis.

included models for the expected distribution of the galactic diffuse emission (based on the known gas distributions) and also empirical modeling using a superposition of one or more sources. Models for PSR 1951+32 (located 2.6° away from Cyg X-1) were also included in the analysis. This pulsar has been detected by EGRET and there is evidence (based on a joint timing and spatial analysis) for it in the COMPTEL data as well (Kuiper et al. 1998). Variations in the derived flux using different spatial models provided a handle on the systematic uncertainties in the analysis.

The COMPTEL data for Cyg X-1 (accumulated from the viewing periods listed in Table 1) shows clear evidence for emission extending out to at least 2 MeV and perhaps as high as 5 MeV. The COMPTEL data alone can be modeled as a power law spectrum with a photon index of -3.7. Good fits can also be obtained using Comptonization models (with electron temperatures in the range of 450-700 keV), but the extrapolation of these fits to lower energies is quite poor. The COMPTEL spectrum is shown along with contemporaneous BATSE and OSSE data in Figure 1. The BATSE spectrum in this case was derived using the JPL Enhanced BATSE Occultation Package (EBOP; Ling et al. 1997b.) These lower-energy data provide the constraints needed for a more effective interpretation of the COMPTEL data.

4 Discussion:

The COMPTEL data alone seems to further corroborate the conclusion that standard thermal Comptonization models may be inadequate in describing the observed spectrum – Comptonization models fall off far too rapidly near 1 MeV (see also McConnell et al., 1994; Ling et al. 1997a). Fits to the combined

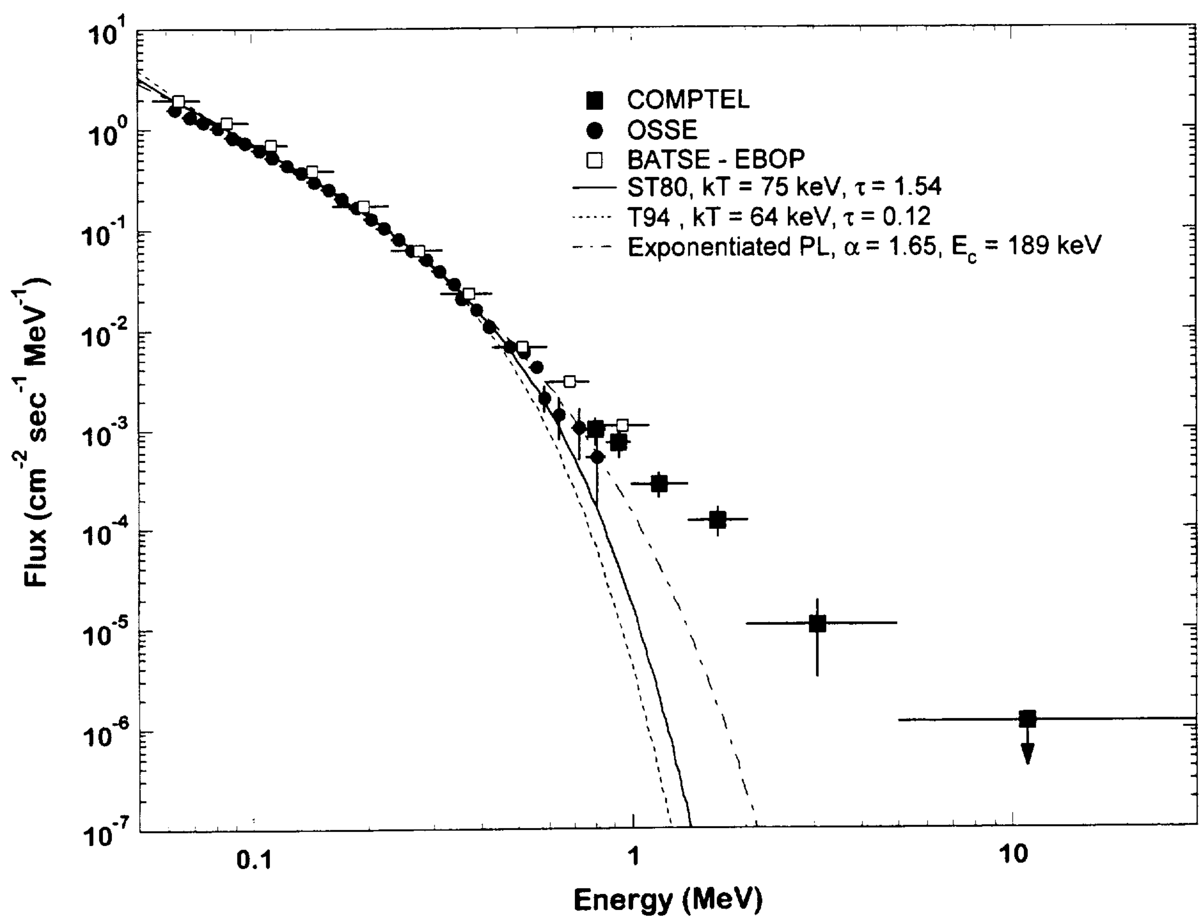

Figure 2: The broad-band spectrum of Cyg X-1 as measured by BATSE, OSSE and COMPTEL. Upper limit data points for BATSE and OSSE have been removed for clarity.

BATSE/OSSE/COMPTEL data provide further evidence for this conclusion. In Figure 2, we show the best-fit spectra (over the full range from 50 keV to 5 MeV) based on the Comptonization model of Sunyaev & Titarchuk (1980), the generalized Comptonization model of Titarchuk (1994) and an empirical fit using an exponentiated power-law (c.f. Phlips et al. 1996). Although the Sunyaev & Titarchuk (1980) model provides a better broad-band fit to the data, the resulting parameters lie outside the range of applicability for this model (Skibo et al. 1995). The model of Titarchuk (1994) may therefore provide a more physically correct fit to the data. Improved fits with the Comptonization models can be obtained by limiting the fit to energies above ~300 keV. The fits obtained by fitting only at energies above 300 keV may, in the context of the reflection models, be a more realistic estimate of the electron temperature, since reflection would contribute to the spectrum only at energies below ~300 keV. On the other hand, several other models can also produce a hard tail feature near 1 MeV without the need for a reflection component. These include both the two-temperature models (Skibo & Dermer 1995; Ling et al. 1997a; Hua, Ling & Wheaton 1997; Moskalenko, Collmar & Schönfelder 1998) and nonthermal models which involve inverse Comptonization of an electron population consisting of both a Maxwellian and some non-Maxwellian distribution (e.g., Li, Kususnose & Liang 1996; Crider et al. 1997). Continued analysis of these data may help shed light on the underlying nature of the high energy emissions from Cyg X-1 and other black hole sources, such as GRO J0422+32, which also shows evidence for a hard tail near 1 MeV (van Dijk et al. 1995).

5 Ackowledgements:

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The Spectral Variability of Cygnus X-1 at MeV Energies

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Abstract. In previous work, we have used data from the first three years of the CGRO mission to assemble a broad-band γ-ray spectrum of the galactic black hole candidate Cygnus X-1. Contemporaneous data from the COMPTEL, OSSE and BATSE experiments on CGRO were selected on the basis of the hard X-ray flux (45–140 keV) as measured by BATSE. This provided a spectrum of Cygnus X-1 in its canonical low X-ray state (as measured at energies below 10 keV), covering the energy range from 50 keV to 5 MeV. Here we report on a comparison of this spectrum to a COMPTEL-OSSE spectrum collected during a high X-ray state of Cygnus X-1 (May, 1996). These data provide evidence for significant spectral variability at energies above 1 MeV. In particular, whereas the hard X-ray flux *decreases* during the high X-ray state, the flux at energies above 1 MeV *increases*, resulting in a significantly harder high energy spectrum. This behavior is consistent with the general picture of galactic black hole candidates having two distinct spectral forms at soft γ-ray energies. These data extend this picture, for the first time, to energies above 1 MeV.

INTRODUCTION

Observations by the instruments on CGRO, coupled with observations by other high-energy experiments (e.g., SIGMA, ASCA and RXTE) have provided a wealth of new information regarding the emission properties of galactic black hole candidates. An important aspect of these high energy radiations is spectral variability, observations of which can provide constraints on models which seek to describe the global emission processes. Based on observations by OSSE of seven transient galactic black hole candidates at soft γ-ray energies (i.e., below 1 MeV), two γ-ray spectral shapes have been identified that appear to be well-correlated with the soft

X-ray state [1,2]. In particular, these observations define a *breaking* γ-ray spectrum that corresponds to the low X-ray state and a *power-law* γ-ray spectrum that corresponds to the high X-ray state. (Here we emphasize that the 'state' is that measured at soft X-ray energies, below 10 keV.)

At X-ray energies, the measured flux from Cyg X-1 is known to be variable over a wide range of time scales, ranging from msec to months. It spends most of its time in a low X-ray state, exhibiting a breaking spectrum at γ-ray energies that is often characterized as a Comptonization spectrum. In May of 1996, a transition of Cyg X-1 into a high X-ray state was observed by RXTE, beginning on May 10 [3]. The 2–12 keV flux reached a level of 2 Crab on May 19, four times higher than its normal value. Meanwhile, at hard X-ray energies (20-200 keV), BATSE measured a significant *decrease* in flux [4]. Motivated by these dramatic changes, a target-of-opportunity (ToO) for CGRO, with observations by OSSE, COMPTEL and EGRET, began on June 14 (CGRO viewing period 522.5). Here we report on the results from an analysis of the COMPTEL data from this ToO observation.

OBSERVATIONS AND DATA ANALYSIS

COMPTEL has obtained numerous observations of the Cygnus region since its launch in 1991, providing the best available source of data for studies of Cyg X-1 at energies above 1 MeV. Figure 1 shows a plot of hard X-ray flux, as obtained from BATSE occultation monitoring, for each day in which Cyg X-1 was within 40° of the COMPTEL pointing direction.

In previous work, we have compiled a broad-band spectrum of Cyg X-1 using contemporaneous data from BATSE, OSSE and COMPTEL [5,6]. The observations were chosen, in part, based on the level of hard X-ray flux measured by BATSE, the goal being to ensure a spectral measurement that corresponded to a common spectral state. In Figure 1, the data points from the selected observations are indicated by open diamonds. The resulting spectrum, corresponding to a low X-ray state, showed evidence for emission out to 5 MeV. The spectral shape, although consistent with the so-called breaking spectral state [1,2], was clearly not consistent with standard Comptonization models. The COMPTEL data provided evidence for a hard tail at energies above $\sim$1 MeV that extended to perhaps 5 MeV.

During the high X-ray state observations in May of 1996 (VP 522.5), COMPTEL collected 11 days of data at a favorable aspect angle of 5.3°. The hard X-ray flux for these days is denoted by open triangles in Figure 1. An analysis of COMPTEL data from this observation revealed some unusual characteristics. The 1–3 MeV image (Figure 2) showed an unusually strong signal from Cyg X-1 when compared with other observations of similar exposure. The flux level was significantly higher than the average flux seen from earlier observations [5,6]. In the 1–3 MeV energy band, the flux had increased by a factor of 2.5, from $8.6(\pm 2.7) \times 10^{-5}$ cm^{-2} s^{-1} MeV^{-1} to $2.2(\pm 0.4) \times 10^{-4}$ cm^{-2} s^{-1} MeV^{-1}. The observed change in flux is significant at a level of 2.6σ. In addition, unlike in previous measurements, there

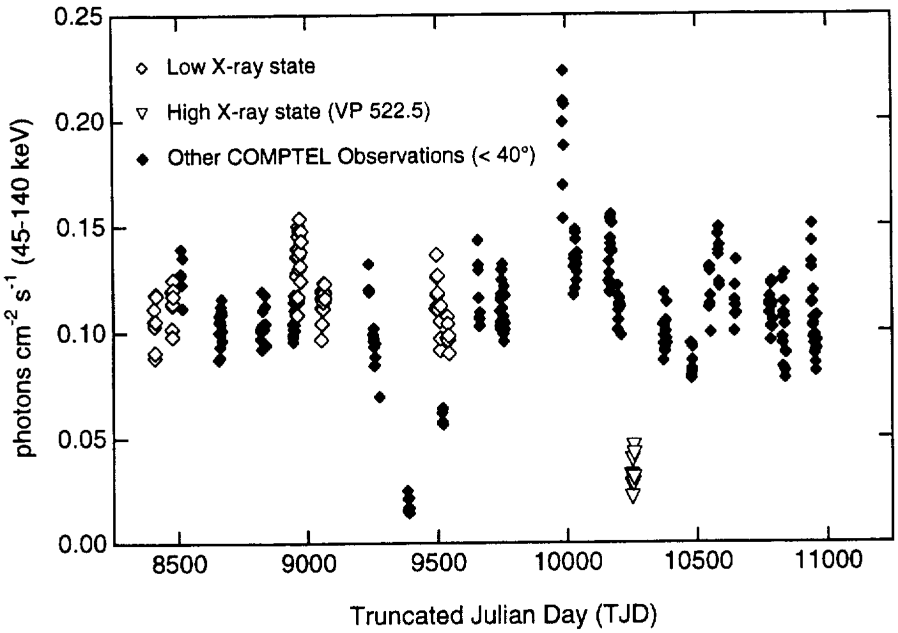
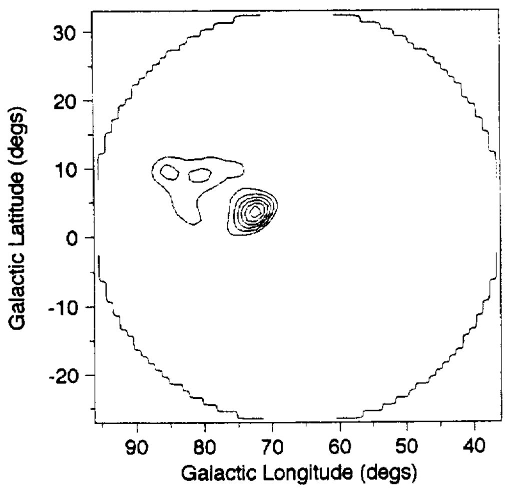


FIGURE 1. Hard X-ray time history (from 45–140 keV BATSE occultation data) for COMPTEL observations of Cyg X-1. Open diamonds indicate those data used to generate the low-state γ-ray spectrum. Open triangles correspond to CGRO viewing period 522.5.

was no evidence for any emission at energies *below* 1 MeV. This fact is explained, in part, by a slowly degrading sensitivity of COMPTEL at energies below 1 MeV due to increasing energy thresholds in the lower (D2) detection plane. Part of the explanation, however, appears to be a much harder source spectrum.

A more complete picture of the MeV spectrum is obtained by combining the COMPTEL results with results from OSSE, extending the measured spectrum down to ~50 keV. Unfortunately, a comparison of the COMPTEL and OSSE spectra for VP 522.5 shows indications for an offset between the two spectra by about a factor of two, with the OSSE flux points being lower than those of COMPTEL in the overlapping energy region near 1 MeV. A similar offset between OSSE and COMPTEL-BATSE is also evident in the contemporaneous low soft X-ray state spectrum [5,6]. The origin of this offset is not clear. Here we shall assume that there exists some uncertainty in the instrument calibrations and that this uncertainty manifests itself in a global normalization offset. We have subsequently increased the flux for each OSSE data point by a factor of two. This provides a good match between COMPTEL and OSSE at 1 MeV for both the low-state and high-state spectra, but we are left with an uncertainty (by a factor of two) in the absolute normalization of the spectra.

We compare the resulting COMPTEL-OSSE spectra in Figure 3 (with the data points in both OSSE spectra increased by a factor two). The low-state spectrum shows the breaking type spectrum that is typical of most high energy observations



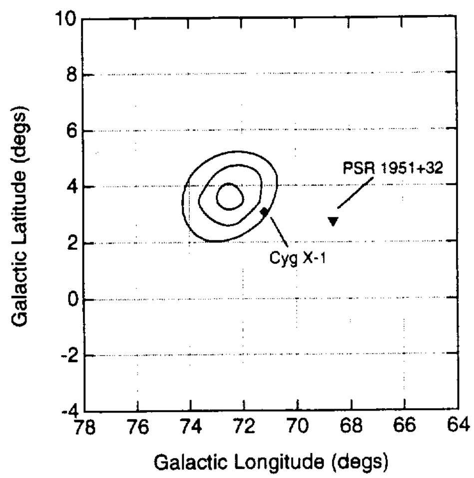


FIGURE 2. COMPTEL imaging of the Cygnus region as derived from 1–3 MeV data collected during high X-ray state of VP 522.5. The left-hand figure shows the maximum likelihood map. The right-hand figure shows the 1, 2 and 3-σ location contours. The emission is consistent with a point source at the location of Cyg X-1, with no significant contribution from PSR 1951+32.

of Cyg X-1. The high-state spectrum, on the other hand, shows the power-law type spectrum that is characteristic of black hole candidates in their high X-ray state. This spectral behavior had already been reported for this time period based on observations with both BATSE [7] and OSSE [8]. The inclusion of the COMPTEL data provides evidence, for the first time, of a continuous power-law (with a photon spectral index of -2.6) extending beyond 1 MeV, up to $\sim$10 MeV.

A power-law spectrum had also been observed by both OSSE and BATSE during February of 1994 [9,10], corresponding to the low level of hard X-ray flux near TJD 9400 in Figure 1. In this case, however, the amplitude of the power-law was too low for it to be detected by COMPTEL.

DISCUSSION

We can use the COMPTEL data alone to draw some important conclusions regarding the MeV variability of Cyg X-1. Most importantly, the flux measured by COMPTEL at energies above 1 MeV was observed to be higher (by a factor of 2.5) during the high X-ray state (in May of 1996) than it was during the low X-ray state. The lack of any detectable emission below 1 MeV further suggests a relatively hard spectrum.

Inclusion of the OSSE spectra clearly show an evolution from a breaking type spectrum in the low X-ray state to a power-law spectrum in the high X-ray state. The COMPTEL data are consistent with a pivot point near 1 MeV. The power-law appears to extend to $\sim$10 MeV with no clear indication of a cut-off.

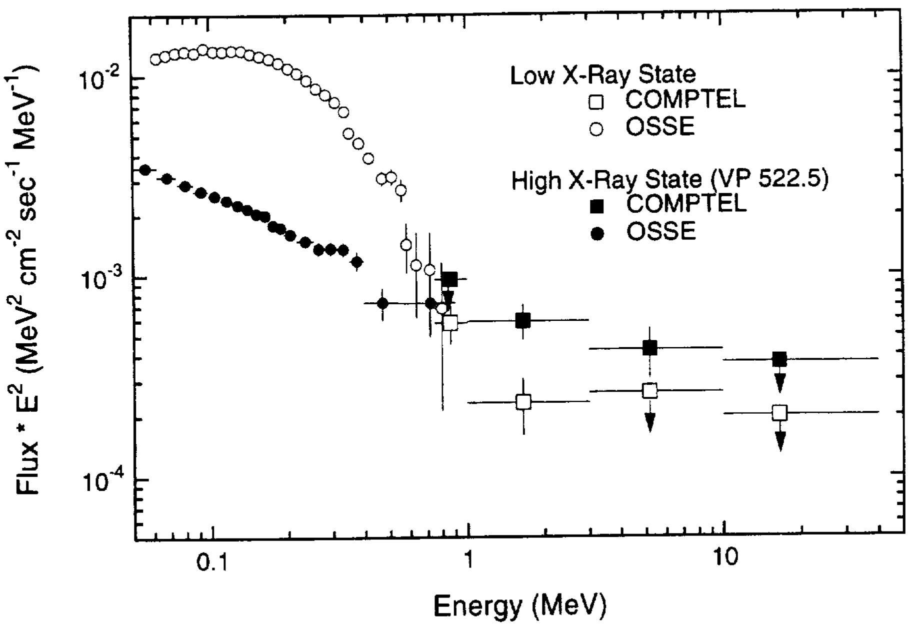


FIGURE 3. Spectra of Cyg X-1, shown as E^2 times the photon flux. OSSE flux levels have been increased by a factor of two and OSSE upper limits have been removed for the sake of clarity.

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